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ASSESSMENT OF J-R CURVES OBTAINED FROM PRECRACKED CHARPY SAMPLES

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J-R curves were determined for five materials (7075-T651; 2024-T351; HY130; HY80; and A723, Class 1, Grade 4) using precracked Charpy samples and standard size C(T) and SE(B) samples. Crack growth in the Charpy samples was estimated using the "load drop" method of analysis of the load displacement trace, and crack extension in the C(T) and SE(B) specimens was determined using the electric potential method. The results show that physical crack extension in

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20. ABSTRACT (CONT'D)

the larger sample was not well estimated by the Charpy sample results. However, if the crack extension is presented as relative crack growth (as a percentage of the uncracked ligament), the agreement between the two widely different specimen sizes is much better, although not exact. With the exception of the relatively brittle 7075-T651, the J corresponding to zero, one percent, and two percent crack growth was higher in the Charpy samples than in the larger samples. This was attributed to the inability of the "load drop" method to determine the exact location of the crack initiation. Although nonconservative, we believe the "load drop" method analysis of precracked Charpy data is adequate for quality control toughness testing provided that it is realized that J_{Ic} and J-R curves may be overestimated slightly.

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INTRODUCTION

Recent work has demonstrated that adequate measurements of crack extension in precracked Charpy samples can be made using its load-displacement characteristics alone (refs 1,2). The method has been called the "load drop" method and is a simplified "key curve" analysis (ref 3). The purpose of this report is to compare the J-R curves generated using the precracked Charpy samples with J-R curves generated with standard size compact tension C(T) or bend samples SE(B) using accurate crack extension measurement methods.

To estimate crack extension using the "load drop" method, the basic assumption is that substantial plastic deformation occurs on the uncracked ligament, such that the maximum load (P_{max}) generated during the test approaches the limit load. In this case, crack initiation should occur very near P_{max}, and the "load drop" beyond P_{max} should be related to the amount of crack extension by (refs 1,2):

$$\frac{P_{\Delta a}}{P_{max}} = \frac{{b_{\Delta a}}^2}{{b_o}^2} \tag{1}$$

Where b_o is the original uncracked ligament dimension; $b_{\Delta a}$ is the uncracked ligament after an increment of crack extension, Δa, ($b_{\Delta a} = b_o - \Delta a$); and $P_{\Delta a}$ is the load beyond P_{max} where the estimate of crack extension is made. This method has proven an adequate approximation of crack extension in several materials (refs 1,2).

[1]Kapp, J. A. and Underwood, J. H., "Single Specimen J-Based Fracture Toughness Test for High Strength Steels," ASTM STP 791, ASTM, 1983, pp. II-401-II-414.
[2]Kapp, J. A., "J-R Curve Determination Using Precracked Charpy Specimens and the Load-Drop Method for Crack Growth Measurements," Fracture Mechanics: 16th Symposium, (M. F. Kanninen and A. T. Hopper, eds.), ASTM STP 868, ASTM, Philadelphia, PA, 1985, pp. 281-292.
[3]Ernst, Hugo, Paris, P. C., Rossow, Mark, and Hutchinson, J. W., "Analysis of Load-Displacement Relationships to Determine J-R Curve and Tearing Instability Properties, ASTM STP 677, ASTM, 1975, pp. 581-599.

To compare how J-R curves generated using small samples agree with larger sample measurements, C(T) and SE(B) specimens were obtained from the same stock from which the Charpy samples were made. The larger samples were of standard planar dimensions W = 2.0 in. (5.08 cm), and thickness, B, was 0.9 in. (2.29 cm). Crack extension was determined using the direct current electric potential method as outlined in Reference 4.

J was calculated for the precracked Charpy sample according to the familiar form (ref 5):

$$J = \frac{2A}{Bb_o} \tag{2}$$

where A is the total area under the load displacement curve. Since small amounts of crack extension were encountered in these samples, the correction for crack extension was also small and thus, no correction for crack growth was made. The C(T) and SE(B) samples were tested in an automated facility with computer aided data processing capabilities. For these samples, J was calculated incrementally accounting for crack extension. For the (i+1) increment, J was given as:

$$J_{i+1} = [J_i + (\frac{f(a/W)}{b})_i \frac{A_{i,i+1}}{B}][1 - (\frac{\gamma}{b})_i[a_{i+1} - a_i]] \tag{3}$$

Where J_i is the total J calculated up to the previous increment; $(a_{i+1} - a_i)$ is the increment of crack growth that occurred between the (i+1) and (i)

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[4] Jolles, M. I., "Automated Technique for R-Curve Testing and Analysis," Automated Test Methods for Fracture and Fatigue Crack Growth, (W. H. Cullen, et al, eds.), ASTM STP 877, to be published.

[5] Rice, J. R., Paris, P. C., and Merkle, J. C., ASTM STP 536, ASTM, Philadelphia, PA, 1973, pp. 231-245.

increments; $A_{i,i+1}$ is the area under the load displacement trace between the (i+1) and (i) increments; and

$$\gamma_i = \begin{cases} 1 + 0.76(b_i/W) & \text{for C(T) samples} \\ 1 & \text{for SE(B) samples} \end{cases} \qquad (4)$$

and

$$f(a/W) = 2 \quad \text{for SE(B) samples}$$

$$f(a/W) = 2[(1+\alpha)/(1+\alpha^2)] \text{ for C(T) samples} \qquad (5)$$

where

$$\alpha = [(2a/b)^2 + 2(2a/b) + 2]^{1/2} - [2(a/b) + 1] \qquad (6)$$

Equations (3) and (4) are based on the analysis of Ernst et al (ref 3) and Eqs. (5) and (6) are the tension component correction of the C(T) sample due to Clarke and Landes (ref 6).

All specimens were precracked in accordance with the procedure outlined in ASTM E-813 on J_{Ic} - A Measure of Toughness. The theoretical nominal limit load was determined for each material and the maximum load during fatigue precracking did not exceed 40 percent of the calculated limit load.

MATERIALS TESTED

Five different materials were tested, three steels and two aluminum alloys. The aluminums were 2024-T351 and 7075-T651 and the steels were HY80, HY130, and A723, Grade 1, Class 4 pressure vessel steel. All except the A723

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[3] Ernst, Hugo, Paris, P. C., Rossow, Mark, and Hutchinson, J. W., "Analysis of Load-Displacement Relationships to Determine J-R Curve and Tearing Instability Properties, ASTM STP 677, ASTM, 1975, pp. 581-599.

[6] Clarke, G. A. and Landes, J. D., "Evaluation of the J Integral for the Compact Specimen," JTEVA, Vol. 7, No. 5, September 1979, pp. 264-269.

steel were obtained in plate form and specimens were obtained such that the T-L orientation was tested. Specimens of the A723 steel were obtained from thick hollow cylindrical forgings testing the C-R orientation. The mechanical properties of these materials are given in Table I. These materials were chosen because of the wide range of properties they exhibit and their wide use in fracture critical applications.

TABLE I. MECHANICAL PROPERTIES OF THE MATERIALS TESTED

Material	0.2% Offset Yield Strength (MPa)	Ultimate Strength (MPa)	%RA	%EL
A723, Grade 1 Class 4	1310	1317	4	11
HY80	614	714	66	21
HY130	958	986	68	20
2024-T351	338	483	19	14
7075-T651	514	583	14	11

RESULTS AND DISCUSSION

The J-R curves developed are given in Figures 1 through 5. In all of the figures, the symbols represent the curves developed using the larger samples and the continuous curves are average values from several (usually four) precracked Charpy samples. The crack extension is represented in two ways: first, as a physical crack extension, and second, as a percentage of the original uncracked ligament. The scales were made such that the data for the larger C(T) and SE(B) samples are at the same location on the plot.

The dual representation of the data was made because of the findings in a previous study (ref 1). In that study the value of J that resulted in about one percent crack extension in the precracked Charpy specimens compared favorably with K_{Ic} values in larger specimens. Since K_{Ic} corresponds to between zero and two percent crack extension, the empirical observation that relative crack extension may be the common denominator when comparing toughness measurements in samples of vastly different size was made. Although such an observation may have significant implications in the development of fracture test methods and analysis, we make no claims as to its universal application. It merely seems to work in the testing of Charpy samples using "load drop" analysis. The authors know of no continuum mechanics reason for such a specimen size dependence and caution against the use of "load drop" analysis or relative crack growth analysis to any structure other than precracked Charpy samples without substantial experimental verification of its applicability.

The aluminum results are given in Figures 1 and 2. The 7075-T651 curves (Figure 1) show a very shallow slope suggesting relatively brittle behavior even with very small precracked Charpy specimens. The initiation values of crack extension is well approximated using the "load drop" analysis of the Charpy samples. Comparing the physical crack extension curves, we observe that the precracked Charpy results give a higher value of dJ/da than the larger samples, but when considering crack extension as a percentage of the

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[1]Kapp, J. A. and Underwood, J. H., "Single Specimen J-Based Fracture Toughness Test for High Strength Steels," ASTM STP 791, ASTM, 1983, pp. II-401-II-414.

original uncracked ligament, either sample size gives essentially the same curve. For 2024-T351 we find a substantially tougher material behavior than with 7075-T651. The initiation J values and the slopes of the R-curves are greater using both small and larger samples. The agreement between large sample results and precracked Charpy results is not as good with the previous alloy. This is especially true with the physical crack extension results. For the small samples, the initiation J value is somewhat higher and dJ/da is also much greater. When these same data are plotted as a percentage of the uncracked ligament, the R-curves are in much better agreement. The initial portion of the large specimen curve is overestimated, but once about 1.5 or 2.0 percent crack extension occurs, the agreement is quite good. Furthermore, the SE(B) data seems to give a somewhat greater dJ/da than the C(T) results. This was also seen in other materials that follow. The fact that the precracked Charpy results agree better with the SE(B) than the C(T) data was expected since the precracked Charpy is also an SE(B) sample of significantly smaller dimensions.

The steel results are given in Figures 3 through 5. The A723 steel was originally a hollow cylindrical forging and it was not possible to obtain large SE(B) samples in the proper configuration. Thus, only larger C(T) specimens were tested. As with the 2024-T351 aluminum, "load drop" analysis of precracked Charpy specimens gives a greater initiation J and a much steeper dJ/da when considering physical crack extension. But again, the agreement is improved when crack extension is given as a fraction of the uncracked ligament. Unlike the earlier results, the agreement does not become very good until about 3.5 percent crack extension. This may be somewhat deceiving because SE(B) samples were not tested in the A723 alloy, while they were in the 2024-T351. A direct comparison of the precracked Charpy and C(T) results in 2024-T351 (Figure 2) aluminum also shows that reasonable agreement was not achieved until about five percent relative crack extension. This suggests that if the same trend was observed in A723 steel between SE(B) and C(T) samples, then even better agreement between the large sample results and the precracked Charpy data may have been achieved if larger SE(B) samples of this alloy had been tested.

The fact that the initiation J values are overestimated in both 2024-T351 and A723 is probably due to the assumption that crack extension begins at peak load. In relatively brittle materials, such as 7075-T651, it is likely that P_{max} is closely associated with the onset of crack extension because the load-displacement trace up to maximum load is nearly linear. This suggests global elastic behavior and nonlinearity beyond P_{max} can indeed be only attributed to crack growth. On the other end of the scale dealing with a very ductile material, where the entire uncracked ligament is subjected to plastic deformation, the drop in the load that the sample can support is either due to crack extension or necking. It is the case that falls between the two extremes where inaccuracy would be expected to be maximized. In that instance crack extension commences when the uncracked ligament is partially plastic upon rising load. This may be the case for the 2024-T351 and A723 materials and will be discussed further below.

Returning to our J-R curves, we come to the HY80 results (Figure 4). Again, comparing physical crack extensions, the precracked Charpy samples give a much higher dJ/da property, but in this case, the initiation values are well predicted using either sample. The curves generated representing crack extension as a percentage of original uncracked ligament show that in this case nearly the entire large specimen J-R curve can be very well approximated with the "load drop" precracked Charpy data. Similar results were obtained in HY130 (Figure 5). The large specimen physical crack extension in HY130 was not measured well from physical crack extension of precracked Charpy specimens. Plotting relative crack extension again gives very good agreement between small and large samples. For HY130, the initiation J value of the larger samples was overestimated with the precracked Charpy specimens. In either HY80 or HY130, the best agreement on the relative crack extension J-R curves occurs between about 1.5 and about 5.0 percent relative crack extension.

The original intended purpose of the "load drop" method was to generate a simple estimate of K_{Ic} using small samples that has application as a quality control measure (ref 1). As K_{Ic} is a measure of the stress intensity factor that results in between one and two percent crack extension, we can compare the large specimen and small specimen R-curves at these amounts of relative crack extension. The data reported here was generated using specimens that were precracked to approximately a/W of 0.5. Thus, the relative amounts of crack extension $\Delta a/a_0$ and $\Delta a/b_0$ are approximately the same and can be determined directly from the R-curves (Figures 1 through 5). These comparisons are given in Table II for all the materials tested. In the table

[1]Kapp, J. A. and Underwood, J. H., "Single Specimen J-Based Fracture Toughness Test for High Strength Steels," ASTM STP 791, ASTM, 1983, pp. II-401-II-414.

a single value is given which is the average of four precracked Charpy samples and the average of all of the larger specimen results.

The first general comment that can be made is that the initiation J value is universally overestimated except in the case of the brittle 7075-T651 alloy. This can be explained by the assumption that the crack begins to propagate at maximum load. Probably small amounts of crack extension occur in the 2024-T351 and the A723 alloys prior to peak load. For the higher toughness HY80 and HY130, some crack extension could have occurred at the maximum load. Since both of these alloys strain-harden significantly, crack growth with a fully plastic remaining ligament may occur without the "load dropping" and thus we would not see it without "load drop" analysis.

TABLE II. AVERAGE J VALUES (kJ/m^2) FROM BOTH SMALL AND LARGE SAMPLES AT VARIOUS AMOUNTS OF RELATIVE CRACK EXTENSION

	$\Delta a/a_o$ = 0.0%		$\Delta a/a_o$ = 1.0%		$\Delta a/a_o$ = 2.0%	
Material	Charpy	SE(B) +C(T)	Charpy	SE(B) +C(T)	Charpy	SE(B) +C(T)
7075-T651	8.5	8.1	9.1	9.4	9.7	10.3
2024-T351	16	13	18	15	19	17
A732 Class 1 Grade 4	56	39	64	49	71	58
HY80	177	163	275	231	316	275
HY130	174	128	285	233	349	315

At greater amounts of relative crack extension, the "load drop" method still overestimated the R-curve, although the absolute differences and the relative differences became much less. For example, at one percent crack extension, the J value from the Charpy sample is about twenty to thirty percent higher than the larger samples for all of the materials, except the 7075-T651 where the difference is almost negligible. Similarly, at two percent crack extension, the differences are reduced to between ten and twenty percent for the more ductile materials. If the J values are represented as their K equivalents, the relative differences are reduced by roughly one-half, i.e., ten to fifteen percent at one percent crack extension and five to ten percent at two percent crack extension.

Table III allows the examination of the discrepancies between the small specimen and large specimen data from a specimen size criterion viewpoint. For cracks to grow under J-controlled conditions, the guideline of a, b, and B dimensions of the sample must be greater than 25 J/σ_f, with σ_f the arithmetic average of the yield strength and ultimate strength. For precracked Charpy samples, the remaining ligament, b, is the important dimension, thus the column 25 $J/b_o\sigma_f$. When this quantity is less than one, J-controlled crack growth is assumed to be occurring, when the ratio is greater than unity, the specimen is too small for the J test. The larger samples had b_o which was about five times the b_o dimension of the Charpy samples, thus if the quantity in the table exceeds five, J was not controlling in the larger samples. The final column in the table is the ratio of the average measured peak load P_{max}

to the theoretical limit load P_{LL} of the precracked Charpy sample (ref 5). This gives an indication of crack extension prior to peak load or any strain-hardening effects that would mark crack extension near peak load.

TABLE III. TOUGHNESS COMPARISONS AND VALIDITY CONSIDERATIONS

(Subscript LD = "Load Drop" Charpy Samples, LS = Larger Samples)

Material	$\frac{\Delta a}{a_o} = 0$		$\frac{\Delta a}{a_o} = 1.0\%$		$\frac{\Delta a}{a_o} = 2.0\%$		
	$\frac{J_{LD}}{J_{LS}}$	$\frac{25\ J_{LD}}{\sigma_f b_o}$	$\frac{J_{LD}}{J_{LS}}$	$\frac{25\ J_{LD}}{\sigma_f b_o}$	$\frac{J_{LD}}{J_{LS}}$	$\frac{25\ J_{LD}}{\sigma_f b_o}$	$\frac{P_{max}}{P_{LL}}$
7075-T651	1.05	0.08	0.97	0.08	0.94	0.09	0.51
2024-T351	1.23	0.20	1.20	0.23	1.12	0.24	0.85
A723, Class 1, Grade 4	1.44	0.21	1.31	0.24	1.22	0.27	0.84
HY80	1.09	1.28	1.19	1.99	1.15	2.29	1.15
HY130	1.36	0.90	1.22	1.47	1.10	1.81	1.19

For 7075-T651, 2024-T351, and A723, the size validity criterion is met; the specimen was sufficiently large for J-controlled crack growth. Therefore, using precracked Charpy samples should result in valid R-curves. The fact that the R-curves do not coincide for the 2024-T351 and the A723 materials is probably due to crack initiation occurring not at peak load, but prior to it. This would have the effect of moving the entire precracked Charpy R-curve to the right or point by point addition of that amount of crack extension that

[5]Rice, J. R., Paris, P. C., and Merkle, J. C., ASTM STP 536, ASTM, Philadelphia, PA, 1973, pp. 231-245.

occurred prior to maximum load. If an estimate of that amount of crack growth prior to peak load could be made, then better agreement would result. At this time a simple method of determining that small increment of crack growth is not available.

In the higher toughness HY80 and HY130 steels, crack growth did not occur under J-controlled conditions. According to the guideline in ASTM E-813 on J_{Ic} - A Measure of Toughness, the precracked Charpy R-curves cannot be considered as valid. What is interesting is that the agreement between small and large samples of these materials was as good as the agreement between small and large specimens of the less tough 2024-T351 aluminum and A723 steel. This suggests either that the validity requirement is too restrictive or a coincidence has occurred. Further work on refining the validity criterion would answer this question. In HY80 and HY130 steels, it is clear that significant strain-hardening occurred. The effect of strain-hardening could be crack growth at peak load with no "load drop". This has the same result as the case of crack growth near but prior to peak load, i.e., "load drop" analysis underestimates crack extension. Real crack extension would move the entire R-curve to the right, thus giving better agreement with the large specimen data.

SUMMARY AND CONCLUSIONS

J-R curves were developed for five materials using both standard samples with well-characterized methods of analysis and precracked Charpy samples using "load drop" analysis. The results show that physical crack extension in the larger samples is not well approximated with the precracked Charpy samples. The J values indicated for the onset of crack extension are overestimated significantly with precracked Charpy specimens. If the crack extension data are presented as a fraction of the uncracked ligament, much better agreement is obtained. In this case the "load drop" analysis still overestimates the overall R-curve but to a smaller degree. Comparisons of the standard and "load-drop" J values at one and two percent crack extension show that the "load drop" values are higher by between ten and thirty percent. This was true even in specimens that were invalid according to the recommended size requirements. The overestimate is attributed to inability of the "load drop" method to sensitively determine the onset of crack growth and to the inherent geometry dependence of J-R curves.

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1. Kapp, J. A. and Underwood, J. H., "Single Specimen J-Based Fracture Toughness Test for High Strength Steels," ASTM STP 791, ASTM, 1983, pp. II-402-II-414.
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6. Clarke, G. A. and Landes, J. D., "Evaluation of the J Integral for the Compact Specimen," JTEVA, Vol. 7, No. 5, September 1979, pp. 264-269.

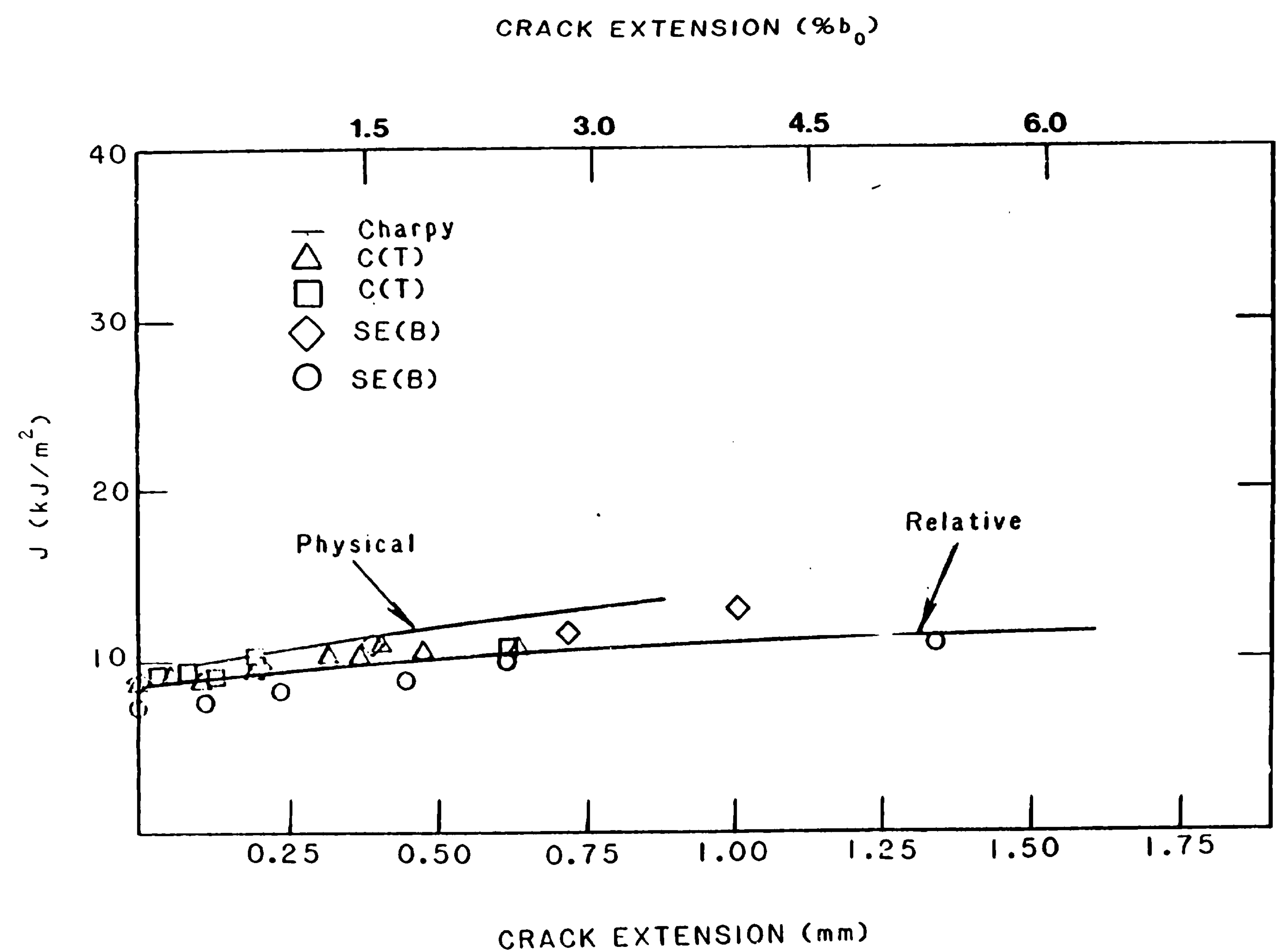

Figure 1. J-R curves for 7075-T651 aluminum.

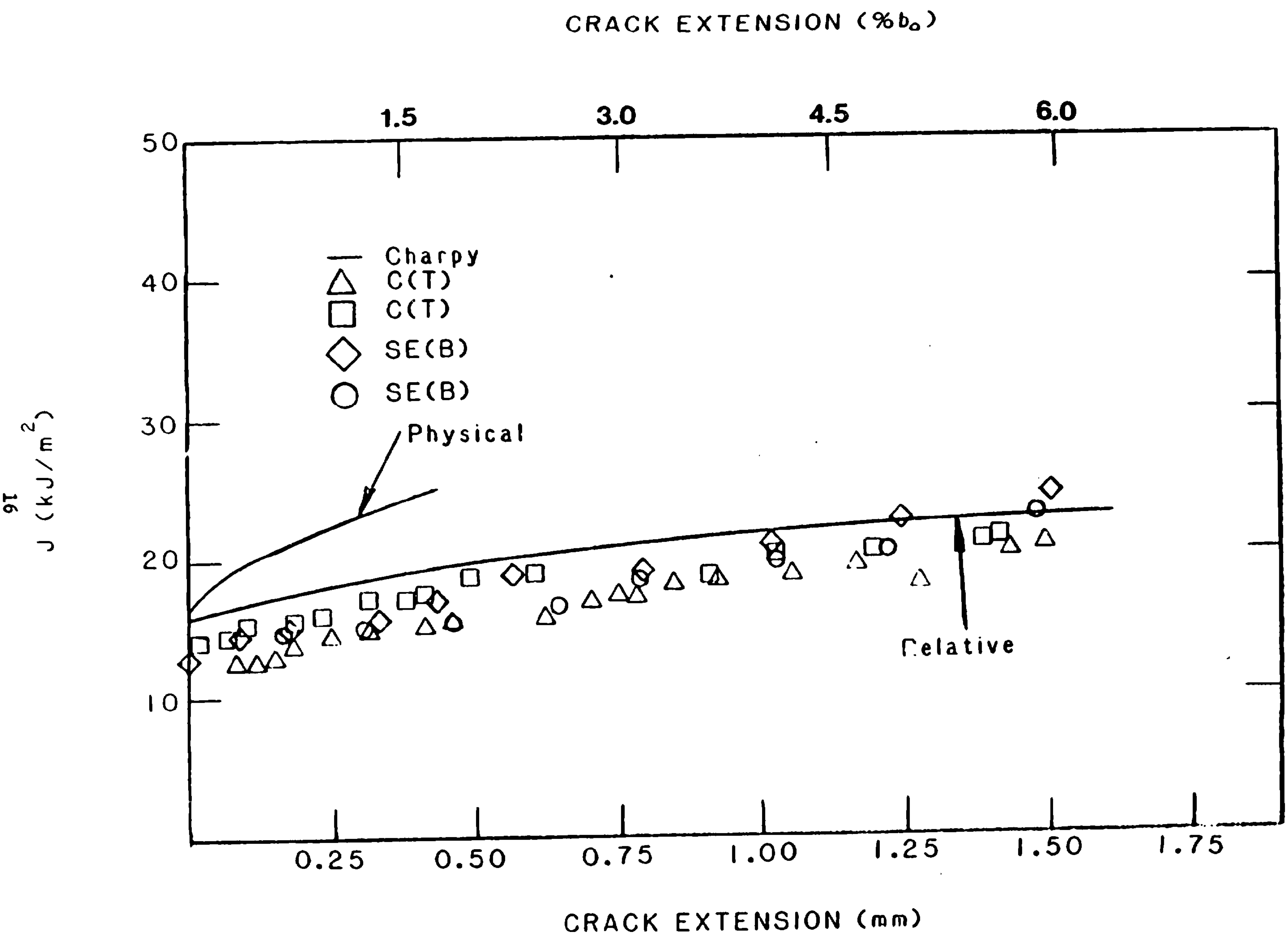

Figure 2. J-R Curves for 2024-T351 aluminum.

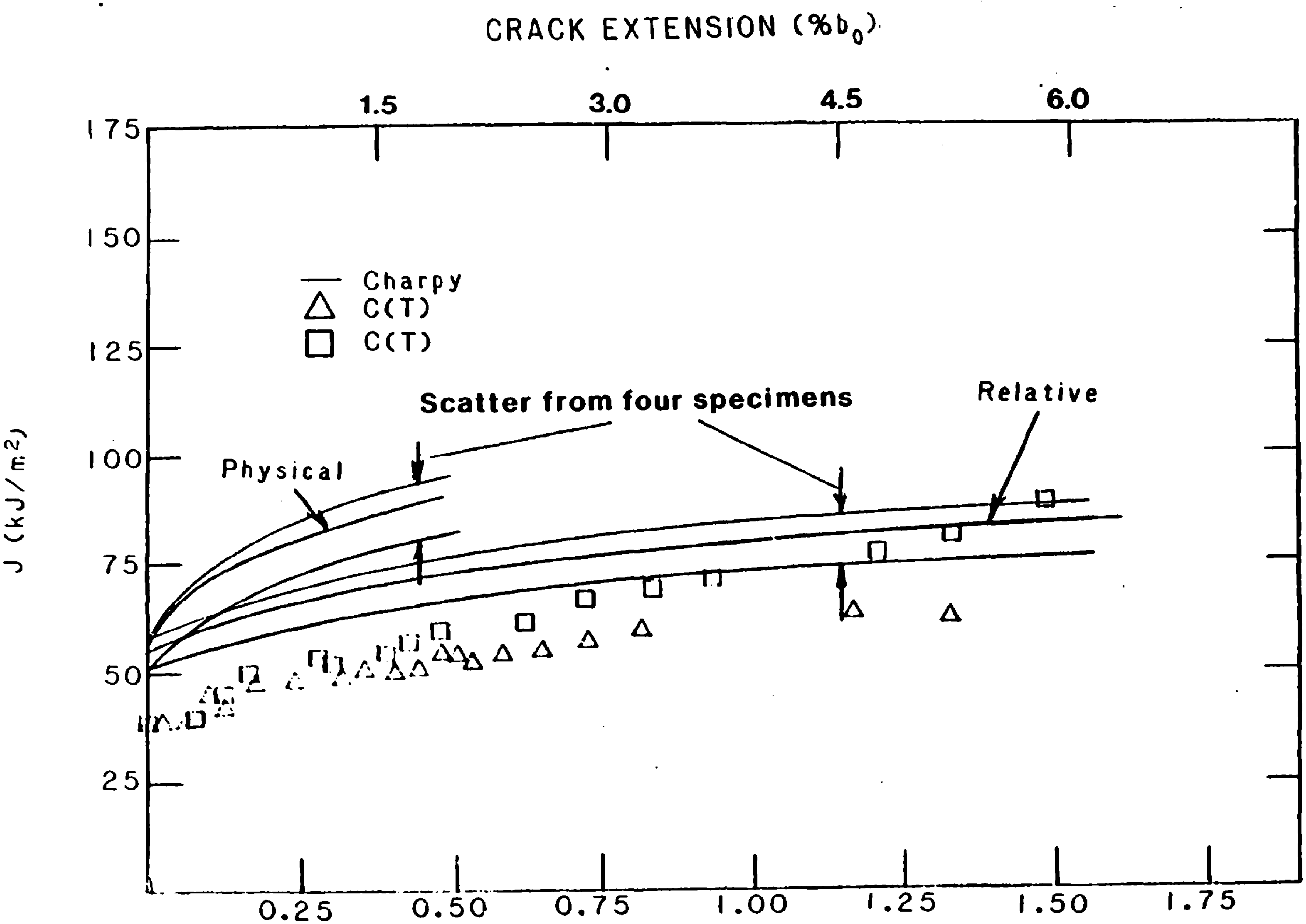

Figure 3. J-R curves for A723, Class 1, Grade 4 pressure vessel steel.

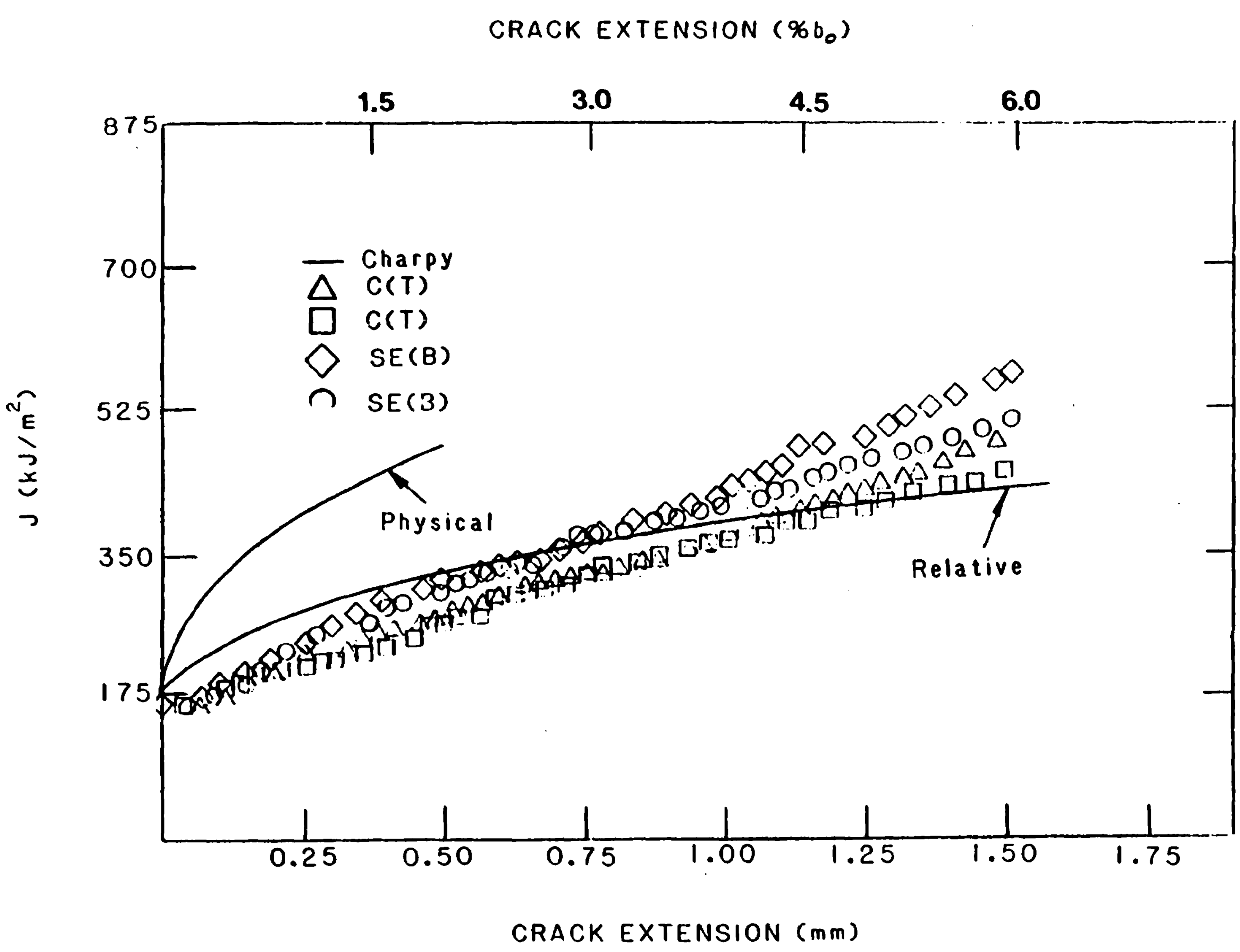

Figure 4. J-R curves for HY80 steel.

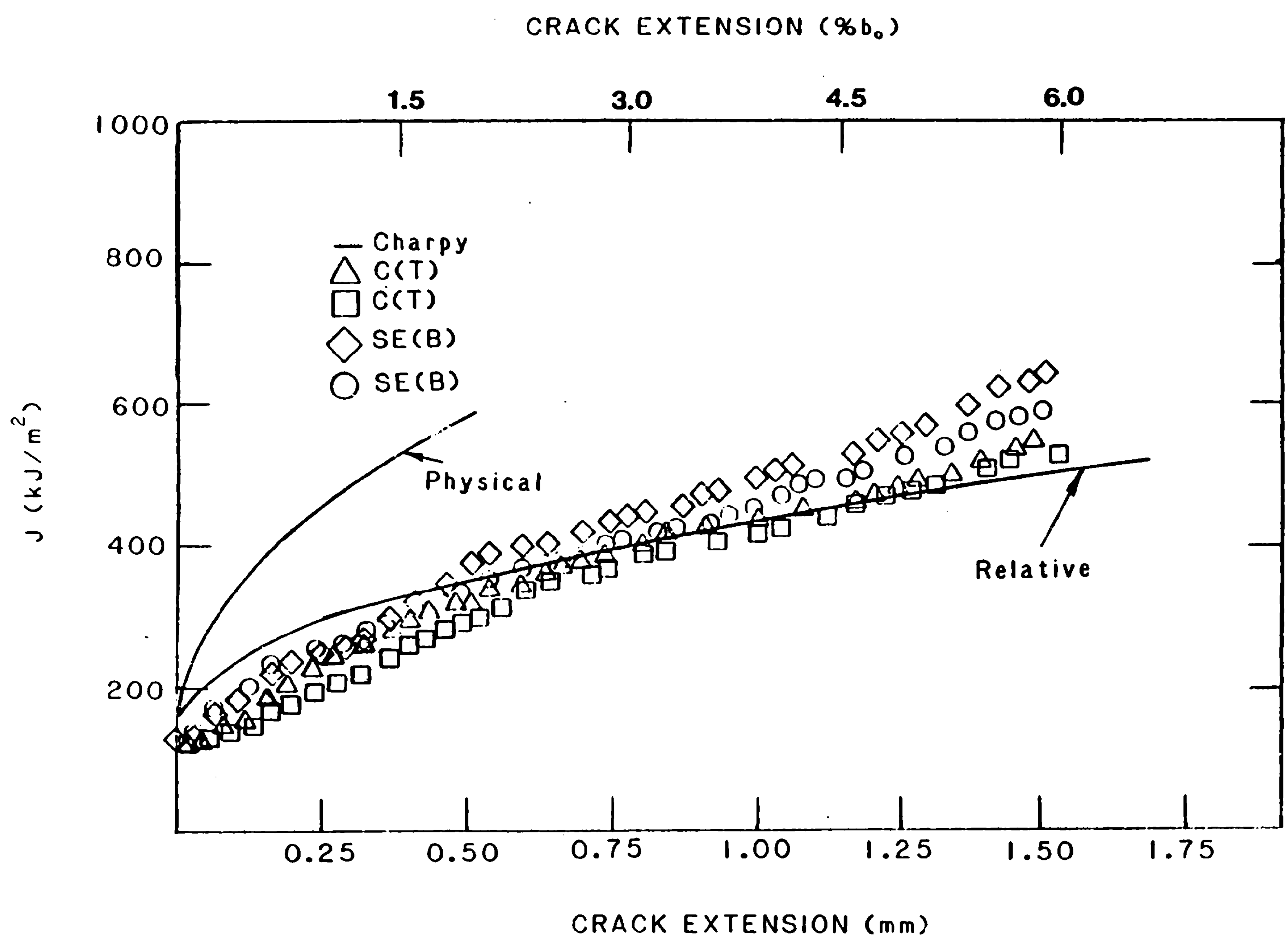

Figure 5. J-R curves for HY130 steel.

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